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A Psychophysical Approach to Dimensional Integrality

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The paper defines dimensional integrality and presents a theory of integrality that explains the manner and conditions under which integrality operates. Integrality is defined as a property of the mapping of a physical specification of complex stimulation into the multi-dimensional psychological characteristics of the stimulation as perceived. An experiment is presented that test this notion of integrality as psychophysical compatibility. Two qualitatively different types of multi-dimensional scaling solutions obtain

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for pair-wise similarity judgments of two sets of triangles. Both sets of stimuli are defined by two physically orthogonal dimensions, but in one set the physical specification is incompatible with the perceived characteristics, and in the other set the physical specification is compatible with the perceived characteristics. This definition of integrality is validated against data obtained from standard information processing tasks involving speeded classification.

THE UNIVERSITY OF MICHIGAN

COLLEGE OF LITERATURE, SCIENCE AND THE ARTS
DEPARTMENT OF PSYCHOLOGY

A PSYCHOPHYSICAL APPROACH TO DIMENSIONAL INTEGRALITY

Robert G. Pachella, Patricia Somers, and Mary Hardzinski

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The purpose of the present paper is to define dimensional integrality and to present a theory of integrality that explains the manner and conditions under which integrality operates. The term integrality, like many pieces of contemporary psychological jargon, has both intuitive and technical meanings. Intuitively, integrality refers to the phenomenological coherence of stimulation. That is, it refers to the degree to which several aspects of complex stimulation are perceivable as a unitary entity. The opposite of integrality, separability, refers to the extent to which each of several aspects of complex stimulation can be independently perceived. As such, integrality, or something like it, represents a core problem within several broad areas of perceptual research such as form perception, pattern recognition, selective attention, information processing and multidimensional scaling. Furthermore, the issues raised about integrality from within these areas vary widely in their generality. Thus, integrality concerns issues as broad and as fundamental as the definition of the stimulus, and as esoteric as the appropriate scaling metric for describing similarity judgments. Consequently, the problems of integrality can be addressed from many different perspectives and discussed in different levels of discourse.

With regard to technical meanings, the multifaceted nature of integrality makes its definition a complicated matter, since different areas of research have specified different operations and phenomena as essential for its understanding. For example, Gestalt Psychology attempted to discover directly and introspectively, those aspects of stimulation that were most closely associated with phenomenal unity. In contrast, modern information processing research, relying on behavioral or performance based data, has focused on the processes within the organism that are responsible

for the ability to selectively attend to various aspects of stimulation. This particular difference in perspective represents one of the primary questions with regard to the study of integrality: Is integrality a property of stimulation, or is it a function of processes within the organism? Undoubtedly, both factors will need to be incorporated into some ultimate definition of integrality. However, as research strategies these two questions are not equally propitious. Stimulation is directly observable and can be objectively defined. Processes within the organism can only be studied indirectly through chains of inference. Furthermore, in the face of finite behavioral data bases, mental processes can never be uniquely defined. Therefore, as a research strategy, the present work will start with an objective examination of stimulation, with the goal of taking this approach as far as it can go. Mental events can then be hypothesized to account for any residual phenomena that still need to be explained.

The theory of integrality to be discussed below will have a purely psychophysical base. Integrality will be defined as a property of the mapping of a _physical_ specification of complex stimulation into the multidimensional _psychological_ characteristics of the stimulation as perceived. This psychophysical mapping will serve as the criterial attribute for deciding whether or not the stimulation in a given situation can be termed integral. This definition of integrality will then be validated against data obtained from standard information processing tasks involving speeded classification.

This account of integrality will be incomplete in at least two ways. First, only one of several psychophysical properties will be explored, and other potentially important, but untested, properties will be suggested in the concluding section. Thus, the research to be reported is only a

first step in what will have to be a broader program of inquiry. Second, this account will also be incomplete in that even from its modest beginning it will be clear that certain aspects of performance will need explanations that will have to go beyond a simple psychophysical theory. These will also be noted in the concluding section. Nevertheless, the present theoretical framework will indicate the direction that additional research will need to take.

Historical Precedents

Gestalt Psychology is, of course, well known for its account of the phenomenological unity of figures in the perceptual field. With regard to the concepts to be developed below, two aspects of the Gestalt approach are of particular importance. First, the Gestalt laws represent an attempt to arrive at a phenomenologically based description of the experience of stimulation. That is, each Gestalt law describes some aspect of experience that tends to be perceived as a unitary whole (i.e. as Gestalten). It is important to note that these laws (Figure-Ground, Closure, Prägnanz, etc.) do not constitute explanations of phenomena, but rather are merely descriptions. The Gestalters' physiological model, now rarely discussed, and their beliefs about physical Gestalten (e.g. the tendency toward equilibrium of forces in physical fields) were the explanations for perceived experience. Nevertheless, these descriptions of experience emphasize that figural coherence is the result of the overall organization of the perceptual field and the complex relations among its perceivable components.

Second, Gestalt Psychology placed a great emphasis on the primacy of perceptual attributes. Theories of perception should begin with phenomenological accounts. To begin accounts of perception with arbitrary physical descriptions of stimulation, as many of the early Structualists did, was thought to be a mistake. Physical descriptions of stimulation should only

follow once the important attributes of experience had been identified. One could conceive of many different physical specifications of stimulation, but the only one that mattered was the one that corresponded to the psychological Gestalten. Of course, the psychological Gestalten were thought to be isomorphic to the underlying physiological Gestalten and these in turn were thought to correspond to physical laws of organization. Thus, because of these isomorphisms, these levels of discourse are sometimes confused. However, within the Gestalt system phenomenology was primary.

This tradition from Gestalt Psychology was further developed by Gibson (1960, 1966) and the research described below is an obvious application of Gibsonian principles. Central to Gibson's approach is the notion of Perceptual Psychophysics: Once a particular perceptual phenomenon has been identified (e.g. monocular depth perception), the study of perception should proceed by finding the physical description of the stimulation that directly corresponds to or is perfectly correlated with the phenomenon (e.g. texture gradients). In many cases this description of physical stimulation may be very complex, entailing higher-ordered or temporal relations among the simple physical variables. However, the goal of perceptual research is the direct specification of this psychophysical mapping.

Strategies of this type have often been pursued in perceptual research. For example, in the area of speech perception there has been a long search to find those characteristics of the physical speech signal that are correlated with the units of perceived speech, the phonemes. Phonemes have certain invariant perceptual characteristics that do not correspond in any simple way to any low-level physical measures of speech. Thus, the search has been to find that combination or transformation of the simple physical characteristics of speech that will correlate reasonably with the stimulation as it is perceived. Similarly, the research dis-

cussed below will examine transformations of the physical measures that underlie particular classes of geometric patterns in an attempt to find those transformations that correspond to the perceived characteristics of the forms.

Multidimensional scaling is a third area of research that is antecedent to the present one. The distinction between integral and separable stimulus dimensions came into prominance with the realization that the psychological distances between pairs of stimuli in a multidimensional space are not necessarily Euclidean. When a subject is asked to judge the similarity of pairs of multidimensional stimuli, his judgments will depend not only on the physically defined differences between the stimuli, but also upon the rule or metric that is used to combine the differences on the several dimensions of the stimuli. Torgerson (1958) suggested that when the several dimensions of a stimulus pair are not obvious, that is, when the dimensions are integral, the Euclidean metric is the appropriate combination rule. This makes intuitive sense, since distance in Euclidean space remains invariant with rotations of the axes of the space; each pair of stimuli thus defines an attribute through the space. For example, the color space invariably has been found to be Euclidean. Each pair of colors, when judged for similarity, seems to define a unique difference between them. In contrast, when the differences among the stimuli are obvious and compelling, that is, when the dimensions are separable, the City Block metric seems more appropriate. Distance in a City Block space is simply the sum of the distances on each of the "obvious and compelling" dimensions. Thus, in arriving at his judgment the subject simply notes the difference on each separable dimension and aggregates them linearly.

This idea of assigning different metrics to integral and separ-

able stimulus dimensions is an important one because it suggests that a multidimensional psychophysical property can be used to define integrality. This suggestion is consistent with the concepts developed below, although the present research will argue that the scaling metric itself is not an adequate criterion.

Previous research in multidimensional scaling has also motivated the present project in another, more fundamental way. Multidimensional scaling depends heavily upon subjects making direct subjective estimations of the similarity between pairs of perceived objects. Similarity judgments thus represent a mode of responding in which subjects can directly code a particular property of their perceptual experiences. As Shepard and Chipman (1970) have noted:

> It is a fact of inadequately appreciated significance that, despite the practically unlimited range and diversity of possible internal representations, we can readily assess within ourselves the degree of functional relation between any two by a simple, direct judgment of subjective similarity. Moreover, we can do this even though (a) we have never before compared the two representations in question, and even though (b) we may be unable to communicate anything about the absolute nature of either of the two representations taken separately...One could even turn the matter around and argue that it is primitive, internal assessments of similarity of this sort...that mediate every response we make to any situation that is not exactly identical to one confronted before. (p. 2)

The psychophysical theory presented below takes this ability of subjects to directly estimate the similarity of pairs of stimuli to be axiomatic. As a psychophysical theory, the description of a psychological space is essential. Consequently, the theory must contain some aspect of subjectivism. However, not only is the subjective component completely identifiable, it is also limited to this primitive ability to assess similarity. Furthermore, whereas the Gestalt approach had to rely on a belief in a first-order isomorphism between properties of stimulation and properties of perceived experience, similarity judgments entail only the notion of second-order

isomorphism (Shepard and Chipman, 1970). That is, it is not necessary that object properties themselves be preserved isomorphically in the internal representation of experience, but only that the relations among the object properties be isomorphically preserved. Thus, it is not necessary to discuss the nature of a given experience itself, rather only the relation of that experience to other experiences, and it is these relations that are directly designated with similarity judgments.

Garner's Converging Operations

The first attempt to produce a systematic theory about the nature and operation of integrality was made by Garner (summarized in Garner, 1974). Garner's approach entails the use of converging operations and their associated phenomena as the definition of integrality. Three of these converging operations are of particular importance. First, for the reasons outlined above, integral dimensions should be best fit by the Euclidean metric when used in similarity scaling. Second, when used in speeded classification or choice reaction time tasks, integral dimensions should produce interference when filtering of one dimension from another is required. For example, if a subject is asked to sort a set of stimuli as fast as possible, where one of two integral dimensions is relevant to the sorting and the other is irrelevant, his inability to separate the dimensions should lead to slower reaction times. By inference, his information processing should be slowed. Third, if a subject is asked to sort a set of stimuli composed of integral dimensions, again as quickly as possible, and the values of the stimuli are correlated across stimuli, that is, if the two dimensions are redundant, reaction time should be facilitated.

A set of stimulus dimensions that produce these three results in these converging tasks, would be termed integral. Conversely, a set of dimensions that would be better fit by the City Block metric, that would

yield no filtering interference and no gain as a result of redundancy, would be defined as separable. Again, there is by inference the linkage of these results to the subject's internal information processing mechanisms: Separable dimensions should not tax the organism's attentive capacity, and his information processing should not slow down or speed up in the presence of irrelevant or redundant information, respectively.

There are two sets of problems that arise with regard to this definition. These problems are for the most part more pragmatic than theoretical, but nevertheless they severly limit the usefulness of the definition. First, there is a set of essentially statistical problems associated with determining the appropriate dimensionality and scaling metric for similarity data. Contemporary scaling techniques utilize computer algorithms that require the experimenter to set a priori the value of the number of dimensions and the scaling metric to be fit to the data. The experimenter then runs the data through the program a number of times, each with a different combination of dimensionality and metric. On each run a measure of goodness of fit, usually referred to as stress, is computed. By comparing these stress values the experimenter can supposedly determine the appropriate parameters for the data. The problem in this, however, is that stress is a monotonic decreasing function of the number of dimensions used to fit the data. Therefore, the experimenter cannot simply look for the minimum stress value. Rather, the function relating stress to the number of dimensions must be examined with the hope that an unambiguous breaking point or "elbow" can be determined. The number of dimensions associated with this elbow is taken to be the dimensionality of the perceptual space for the stimuli in question. The stress value for each metric for this number of dimensions can then be compared, with the better fitting metric chosen as the appropriate one.

Three difficulties, however, can render this solution uninterpretable: There may be no obvious elbow; the elbows for each of the metrics may occur

at different dimensionalities; and there are no reasonable statistics that assess how big a difference in stress values is reasonable. Often more than one of these problems exist for the same set of similarity judgments. Consider the data presented in Figure 1. These data, from Hardzinski and Pachella (1977), are based on similarity judgments for 32 simple ellipses that varied in their size and shape, and their spatial position and orientation on the viewing screen. All 496 pairs of ′ .e 32 stimuli were judged for similarity and these judgments were analyzed with the scaling program MINISSA (Guttman, 1968; Roskam and Lingoes, 1970). It is clear from Figure 1 that neither curve has a sharp elbow in it. Further, even though the Euclidean metric yields a better fit for each value of dimensionality, the difference between the curves is not impressive. Thus, it is not obvious whether the differences for these stimuli should be called integral or separable. Even more to the point, the scaling configuration of the stimulus points in their respective spaces (i.e. Euclidean vs. City Block) and their interpoint distances did not differ much from each other. Effectively the scaling solutions were identical. Hardzinski and Pachella (1977) worked with numerous types of stimulus forms (ellipses, irregular polygons, schematic faces, etc.) and have found the situation described here to be the rule rather than the exception. Thus, the determination of the appropriate scaling metric is often the result of an entirely subjective judgment on the part of the experimenter.

A second problem with the converging operation definition of integrality is the fact that when the operations used to define the concept do not converge, the result is a proliferation of theoretical terms, each corres-

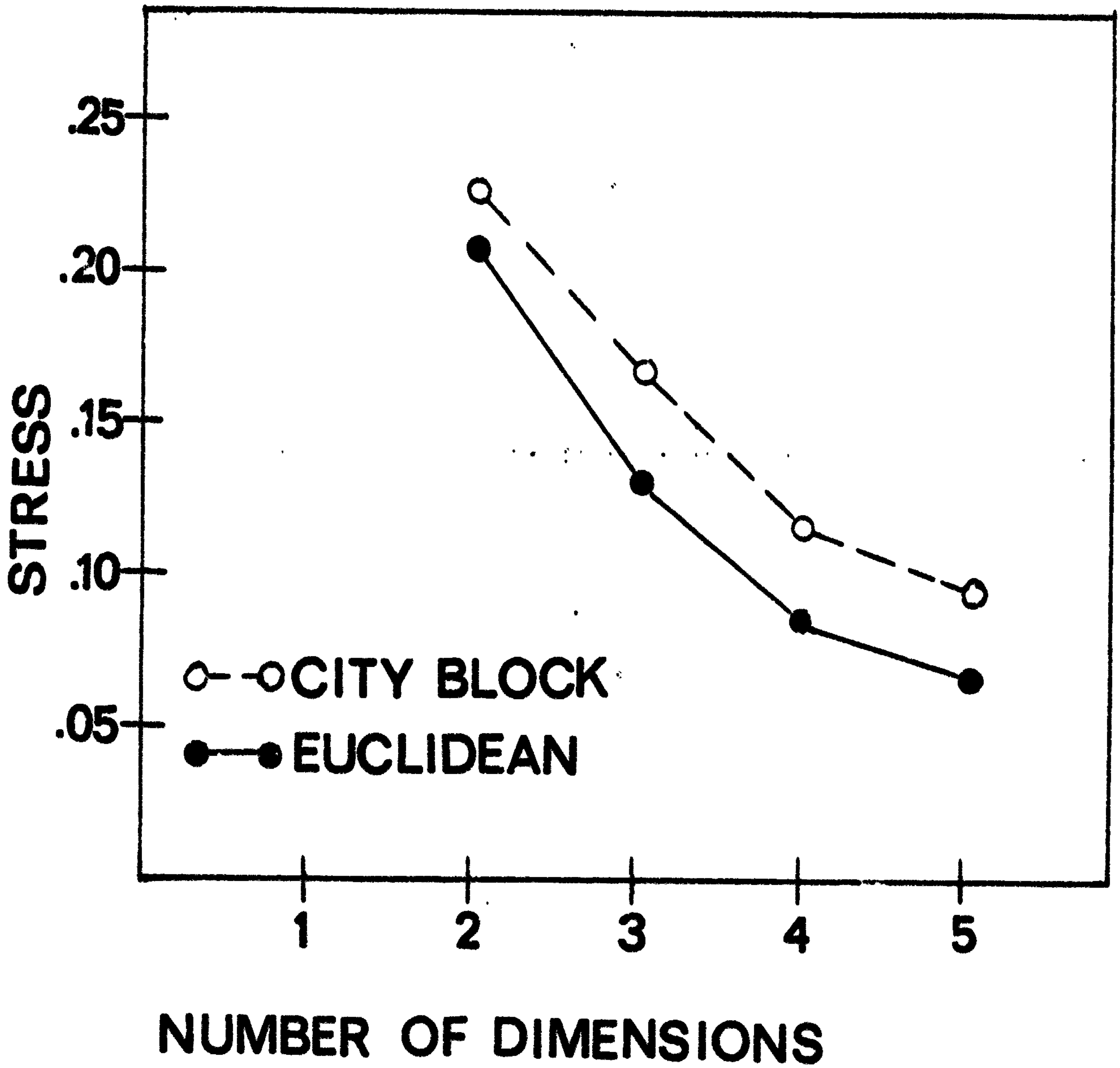


Figure 1: Stress values for multi-dimensional scaling configurations of similarity judgments of pairs of ellipses differing on 5 dimensions, as a function of number of dimensions fit for both Euclidean and City Block metrics.

ponding to a different pattern of results. That is, the multiple operation definition of integrality, with integral dimensions defined by one combination of results and separable dimensions defined by another combination, leaves open the possibility of various intermediate results that are at best difficult to interpret. For example, at least one example exists of phenomenally integral dimensions that are best described by the City Block metric. In another case, Garner and Felfoldy (1970) found that dimensions that should be compellingly Euclidean (vertical and horizontal position in the Euclidean plane) yielded the expected facilitation of reaction time when the dimensions were redundantly varied across stimuli, but surprisingly little interference when filtering was needed to perform a speeded classification task. Such intermediate results have led to a burgeoning taxonomy of integrality types that include "configular dimensions" (Pomerantz and Garner, 1973) and "asymmetric integral dimensions" (Pomerantz and Sager, 1975). This taxonomy thus serves to simply label the different combinations of results without specifying their logical or perceptual relationships.

THE PSYCHOPHYSICS OF INTEGRALITY

The proliferation of types of integrality might lead to the questioning of the unitary nature of integrality as a theoretical concept. An alternative approach to the problem, however, will point out the source of this difficulty. The goal of much previous research has been to discover the property of physical dimensions that leads to their being integral or not. Alternatively, however, attribute perception might be assumed to be invariant. That is, a theoretical account might begin with the assumption that any set of stimuli is definable by an independently identifiable (i.e. separable) set of psychological attributes. What may vary instead is the way in which

the experimenter has defined the physical dimensions whose integrality he is investigating. Integrality may, thus, be simply the result of an inappropriate specification of stimulation.

This alternative account of integrality begins with the observation that there are any number of potential physical descriptions of a stimulus. Consider, for example, the physical specification of a simple triangle. A particular triangle can unambiguously be specified by noting the lengths of its three sides. Alternatively, it can also be specified by the lengths of two sides and one of its angles; or, by two of its angles and one side; or, by its area and the length of two sides; etc. These physical descriptions, although equivalent as physical specifications, will not be equivalent perceptually. Suppose, for example, that the salient and compelling attributes of a triangle are its elongation, its size and its tilt. That is, when an observer perceives a triangle suppose that the psychological attributes that are most compelling are how long it is, its area and its obtuseness (or acuteness). The physical description that would be most relevant perceptually, then, would be that description consisting of physical variables that correlate with these salient features. These physical variables would be "separable" in that changing the value of each would be seen by the observer to change the value of one of the salient attributes.

In contrast, a physical description that would not correspond to these salient attributes would consist of variables that would cut across the perceivable attributes. Consequently, the manipulation of one of the physical variables would be seen by the observer as causing variation in more than one of the perceptual features. Physical variables that would cause variation in the same perceptual attributes would thus be confusable and and would be seen to be "integral".

Salience and Emergence

One consequence of this lack of correspondence between the physical and psychological descriptions is the apparent emergent property of the psychological attributes. If an experimenter focuses his attention arbitrarily on a particular physical description that does not correspond to the psychological attributes, the perceivable attributes will vary as a complex function of the physical variables. Because their value will covary with several different physical variables, the psychological attributes will be seen by the experimenter as being relatively independent of each of the physical variables. Thus they will seeem to the experimenter tc "emerge" from the physical variables.

This emergence will also prove difficult for the subject of an experiment. If the subject is called upon to attend to one of the non-corresponding physical variables, the covariation of the psychological attributes with the irrelevant physical variables will be confusing to the subject. In addition, because of the salience of the psychological attributes the subject will simply be distracted by their variation (see Egeth and Pachella, 1969). In either case the subject's judgments of the relevant variable will be affected either directly by variation in the irrelevant physical variables, or the effect of these variables on the psychological attributes, or both.

Somers and Pachella (1977) examined these effects of salient, apparently emergent attributes on the perception of simple physical variables in complex stimuli. In this experiment observers were asked to rate the degree of similarity of pairs of stimuli with regard to particular selected features. Other features of the stimuli were either held constant (control condition) or varied systematically (experimental condition). The use of similarity judgments, without any stress on speed or difficulty in viewing, allowed the measurement of the

perceptual distortion of the relevant features due to variation of the irrelevant variables. If the observers could ignore the variation of the irrelevant features, the perceived similarities of the stimuli in the experimental and control conditions would be identical. However, if such selective attention was impossible, if the dimensions were integral, the influence of the irrelevant dimension would be revealed in the pattern of the similarity judgments.

In this experiment the subject was asked to rate the similarity of schematic faces (see Figure 2) with regard to the shape of the facial outline. In the experimental condition facial expression varied, but the subject was instructed to ignore it. Figures 3 and 4 present typical data for one observer. The numbers in Figures 3 and 4 are labels for the individual schematic faces that were used in the experiment. The figures summarize the similarity ratings for pairs of faces by representing similarity as interpoint distances. Consequently, faces that were judged to be similar (e.g. faces 12 and 16 in Figure 3) will be close to each other, while faces judged to be dissimilar will be far apart (e.g. faces 9 and 4 in Figure 3). Figure 3 presents the control condition, in which facial expression was not varied within a block. Figure 4 presents the experimental condition. The faces whose numbers are circled were given one facial expression while those represented by uncircled numbers were given a different expression. Note again that the subject was asked simply to judge the similarity of the shapes of the faces in both conditions.

A comparison of Figures 3 and 4 shows that varying facial expression had large and systematic effects on the judged similarity of shape for

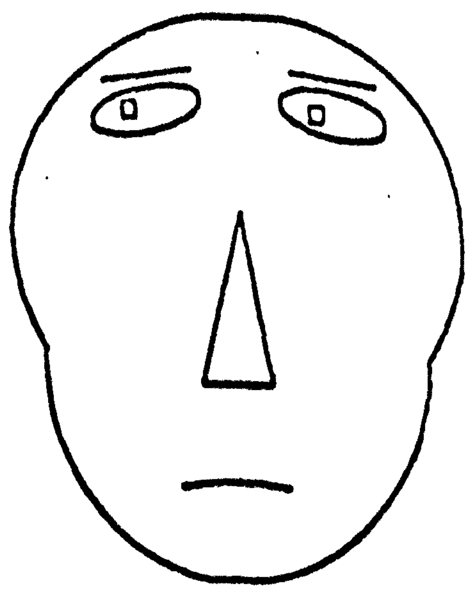


Figure 2: An example of the schematic faces used as stimuli by Somers & Pachella (1977).

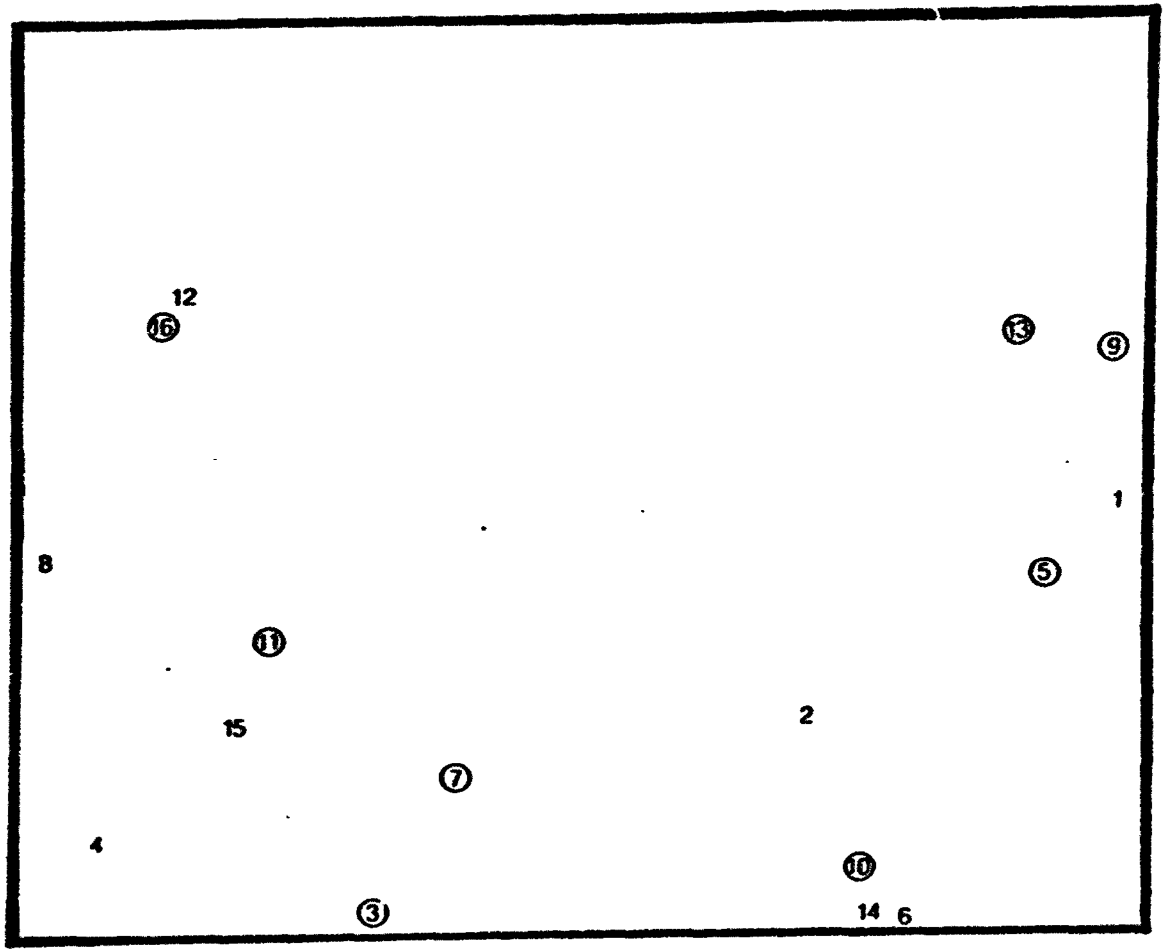


Figure 3: Multidimensional scaling configuration of judged similarity of facial shapes when facial expression was held constant within a block of trials.

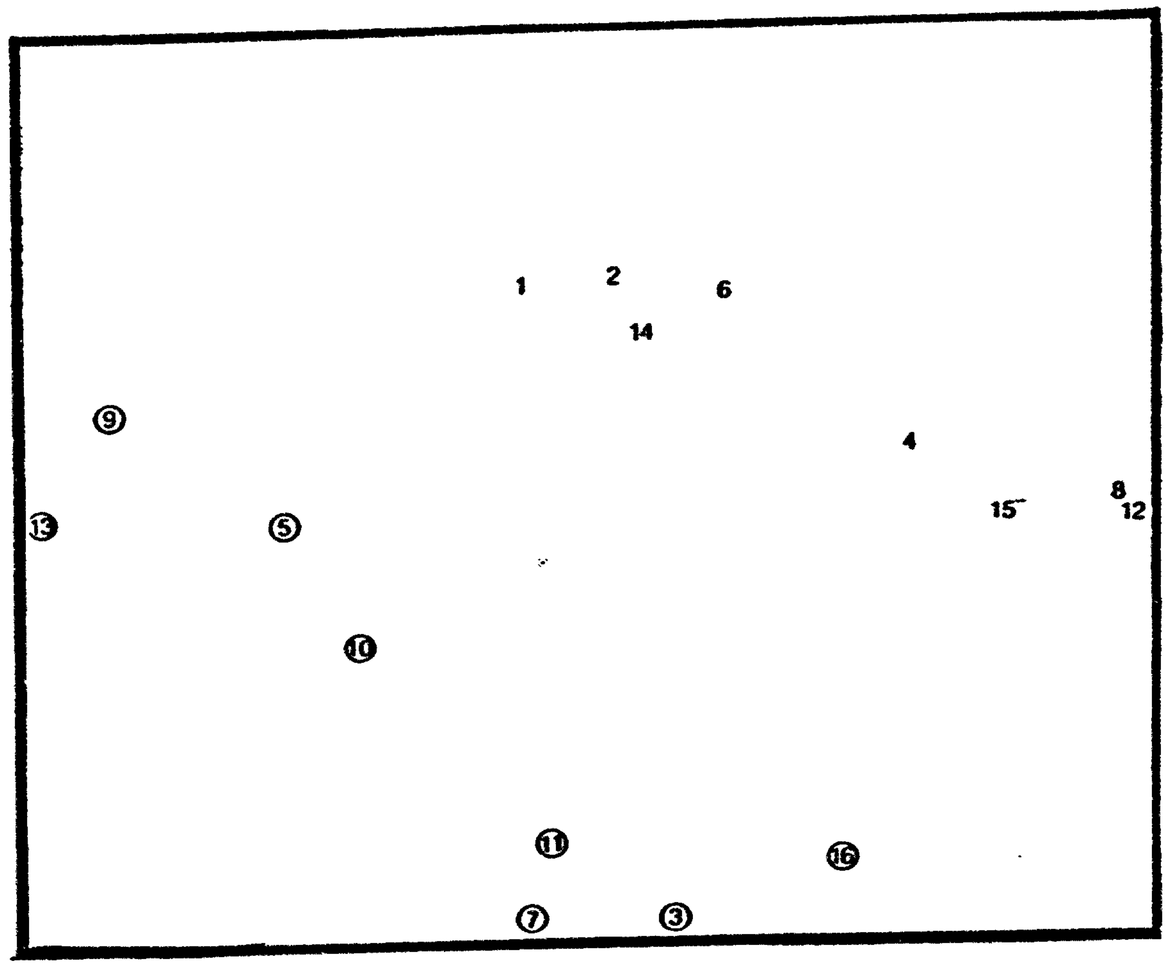


Figure 4: Multi-dimensional scaling configuration of judged similarity of facial shapes when facial expression varied irrelevantly.

this observer. In Figure 4, faces with common expressions are grouped together. The average similarity for pairs within the groups is far greater than the average similarity of pairs from different groups. The observer was simply unable to ignore the facial expression and his rated similarity of facial shape was influenced by this irrelevant information. For example, faces 10 and 6 have quite similar shapes, as shown by their proximity in the control condition. In the experimental condition, where they vary in expression, their shapes are perceived to be much less similar. Thus, although there is a degree of identifiability to the separate features for stimuli such as these schematic faces, such attributes can be shown to be integral.

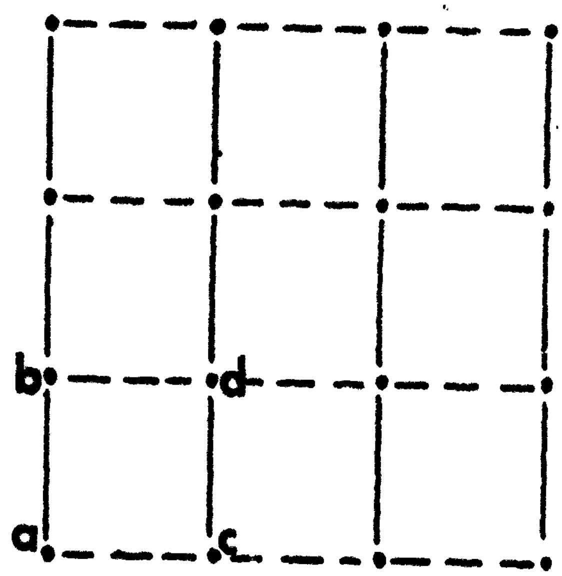
Furthermore, the degree of integrality can be measured directly from Figures 3 and 4. This is done by computing the ratio of the average inter-point distance between faces with similar expressions to the average inter-point distance between faces with different expressions in the experimental condition. The ratio of the analogous distances in the control condition serves as a baseline, since the outline shapes are identical to those in the experimental condition, but facial expression does not vary. Comparing the ratios for the two conditions yields a continuous quantitative scale of integrality. Thus, facial expression which is a complex emergent property of the simple features of the face, is a prepotent attribute in determining the appearance of any of the constituent features of the face, such as its outline shape.

Interdimensional Additivity

The theory of integrality that is being suggested in the present paper is based on the fact that the dimensions that an experimenter varies independently in a set of stimuli are not necessarily perceived to be independent by an observer. An observer will perceive a stimulus from a given stimulus

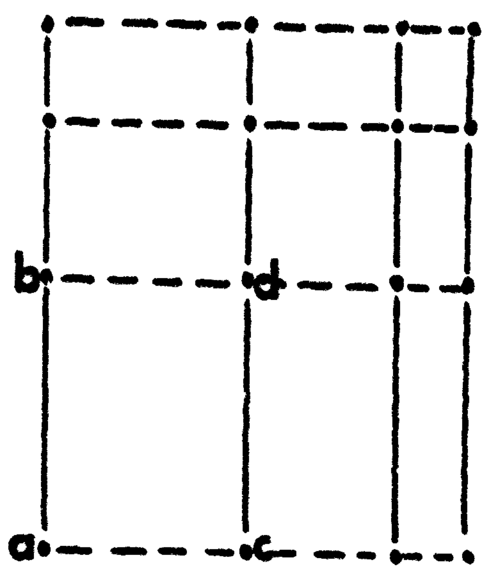
domain as varying along a set of independent psychological dimensions appropriate for that domain, but these attributes are not necessarily varied independently in the specific subset of stimuli presented to him. Perceived attributes must be independent, or separable, by virtue of their definition as attributes. If perceived differences along an attribute vary with the value of another attribute, they will have little value for the consistent perception of similarity. This concept is formalized in the axioms of the geometric models of similarity underlying multidimensional scaling. These axioms, stated by Tversky and Krantz (1970) and Krantz and Tversky (1975), include interdimensional additivity, which states that the perception of similarity among multidimensional stimuli is an additive combination of their similarity along each of their component dimensions.

To clarify the concept of interdimensional additivity, consider Figure 5a. This is a spatial representation of the physical differences among stimuli varied on two orthogonal dimensions such that the more different two stimuli are, the farther apart they lie in the space. The intersections of the lines are the stimuli. Solid lines connect stimuli with equal values on one dimension. Dashed lines connect stimuli with equal values on the second dimension. By definition the dimensions that are physically orthogonal appear as right angles in the space, and the configuration is rectangular. If a spatial representation of the similarity judgments of these stimuli were also rectangular, the two physically orthogonal dimensions would be said to be psychologically additive. Figure 5b displays such a spatial representation. In this figure distance in the space corres-



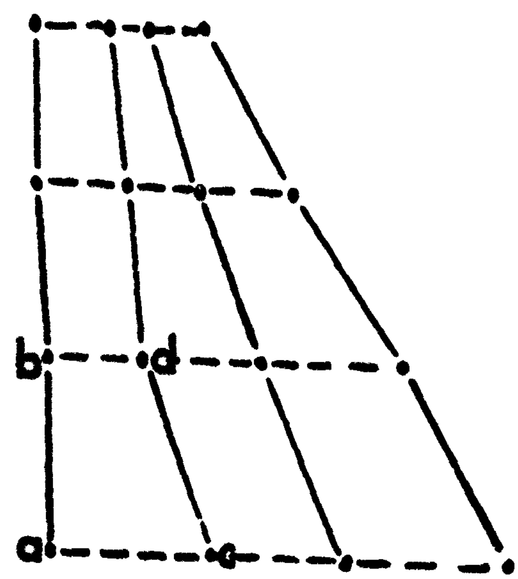
Spatial representation of physical differences among stimuli varying on two physically orthogonal dimensions.

A



Spatial representation of perceived similarity among stimuli of Figure 5a when the physically orthogonal dimensions are perceptually orthogonal.

B



Spatial representation of perceived similarity among stimuli of Figure 5a when the physically orthogonal dimensions interact perceptually.

C

Figure 5

ponds to psychological dissimilarity, not to physical differences. Again, solid and dashed lines indicate the physically orthogonal stimulus dimensions. They are also psychologically orthogonal. Since the physically orthogonal stimulus dimensions correspond to psychologically orthogonal dimensions, the stimulus dimensions would be termed separable. Note that the spacing along each psychological dimension does not correspond to the physical intervals. The values on both of the two dimensions are not equally spaced perceptually, nor are the intervals along one dimension equal to those along the other. This is irrelevant to the question of the interaction between dimensions. The rectangularity of Figure 5b captures the property of interdimensional additivity (Tversky & Krantz, 1970; Krantz & Tversky, 1975) with regard to physically orthogonal dimensions: the dissimilarity between two stimuli is monotonically related to the sum of terms representing the distance between the stimuli on each dimension.

Figure 5c displays an alternative spatial representation of dissimilarity judgments of the stimuli of Figure 5a. Solid and dashed lines again represent physically orthogonal dimensions, but here they psychologically interact. There is a systematic departure from rectangularity in this spatial representation of dissimilarity judgments: equal physical differences along the horizontal dimension are psychologically diminished as the second dimension increases. When physically orthogonal dimensions psychologically interact, as these do, the stimulus dimensions would be termed integral. Another piece of evidence for a violation of interdimensional additivity in this configuration is the consistent inequality of similarities for stimulus pairs that are related diagonally and are therefore physically equal. For example, the physical difference between stimuli labelled _b_ and _c_ in Figure 5 is equivalent to that between _a_ and _d_, as can be seen in Figure 5a. The effect of the psychological interaction in

Figure 5c is to make the pair (b,c) appear more dissimilar than (a,d).

Figure 6 presents an even more concrete example of interdimensional additivity. These triangles are constructed from a common base; that is, the length and orientation of the base has been held constant. Therefore, there are only two degrees of freedom of the physical variation among the set of stimuli, so that any particular stimulus can be uniquely specified by a minimum set of two physical parameters. With regard to interdimensional additivity, the goal is to find the physical parameters of the most perceptually salient attributes of the patterns. Let us consider height and length of right side. The four triangles in Figure 6 were chosen as orthogonal examplars of these dimensions. That is, the triangles in each row have equal values for the length of their right sides, and the triangles in each column have equal heights. However, as perceptual variables the differences in these variables do not look independent. In fact, we have asked observers to judge the similarity of the pairs on the diagonal, that is, on the one hand the pair 10 and 13, and on the other hand, the pair 9 and 14. Invariably observers will note that the pair 9 and 14 look more similar to each other than pair 10 and 13. Note, however, that in terms of the physical differences these two pairs are equally different. It is this lack of correspondence between physical and psychological variables that we have termed integrality because it is clear that the overall similarity of the figures is an interactive function of height and length of right side. Thus, these variables cannot be separated easily by the observer.

In an effort to discover a set of dimensions corresponding more closely

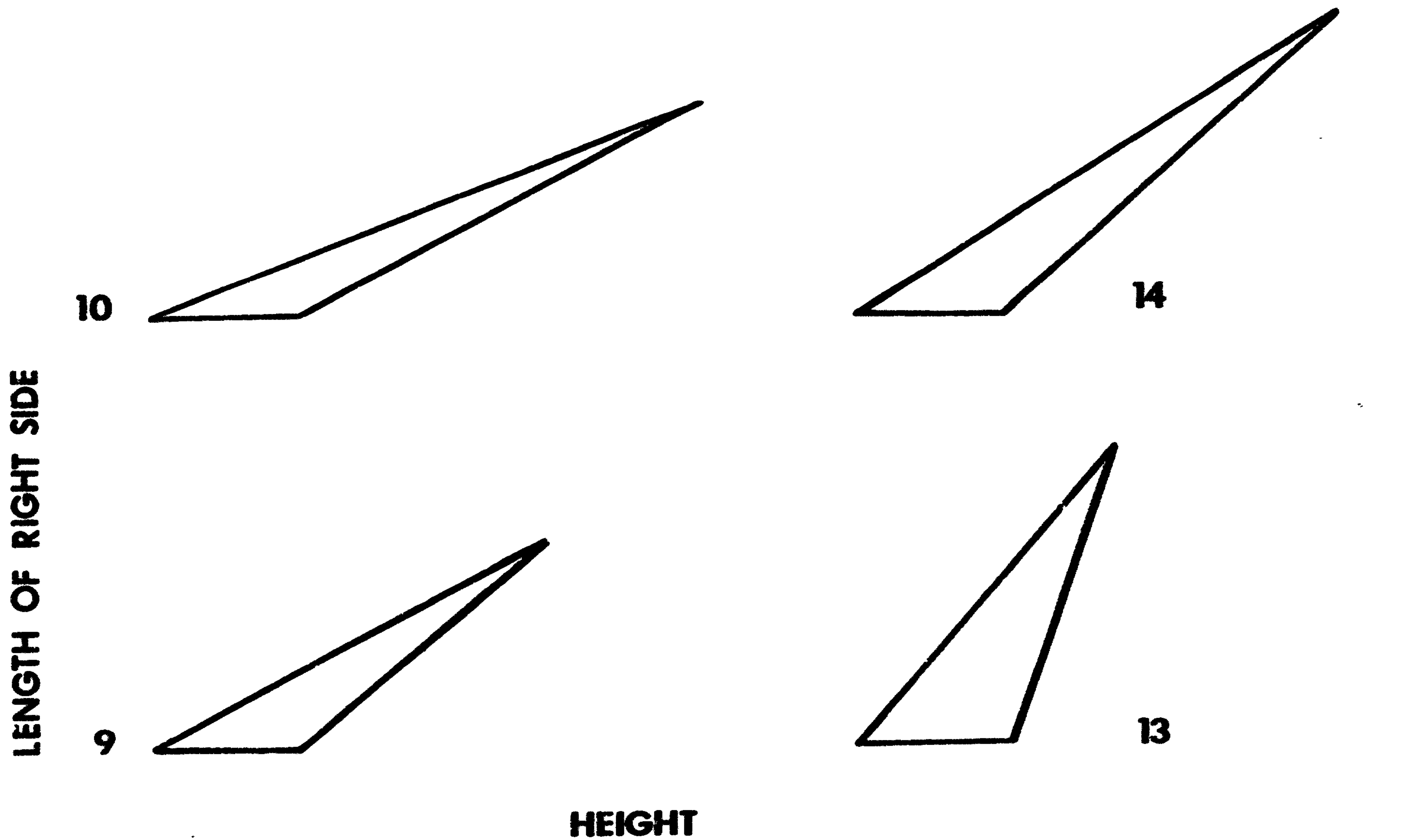


Figure 6; A set of triangles constructed from a common base length. The triangles in each row have equal values for the length of their right sides, and the triangles in each cloumn have equal heights.

to the psychological attributes for this pattern type, we developed a larger set of triangles. Four values of height and four values of the length of the right side were orthogonally combined to create a set of sixteen patterns. Observers were then asked to make similarity ratings for each of the possible pairs of triangles within the set. These ratings were then mathematically transformed into a "map" of the psychological distances between the patterns. Figure 7 shows the typical data of one subject. The solid lines connect triangles that differ from each other only in terms of height (they are equal in length of side). If there had been a high correspondence between these physical dimensions and the perceivable attributes of the figures, this figure would have been rectangular. This was not the case: the pattern of perceived similarities differed markedly from that expected if judgments were based on the orthogonal dimensions.

This fact can be used to construct sets of displays that will be high in psychophysical compatibility. For example, we constructed a set of sixteen triangles that differed from each other orthogonally in terms of a topological transformation of height and length of the right side, on the one hand, and in terms of interior obtuse angle (with a slight correction for length of right side) on the other. The data in Figure 8 show the psychological "map" of the interpoint similarities for the same observer whose data were shown in Figure 7. Again, the solid lines connect triangles that differ from each other only in terms of the product of height and side. The dotted lines connect points that differ only in terms of angle. It is clear that this manipulation has removed the interaction that was present

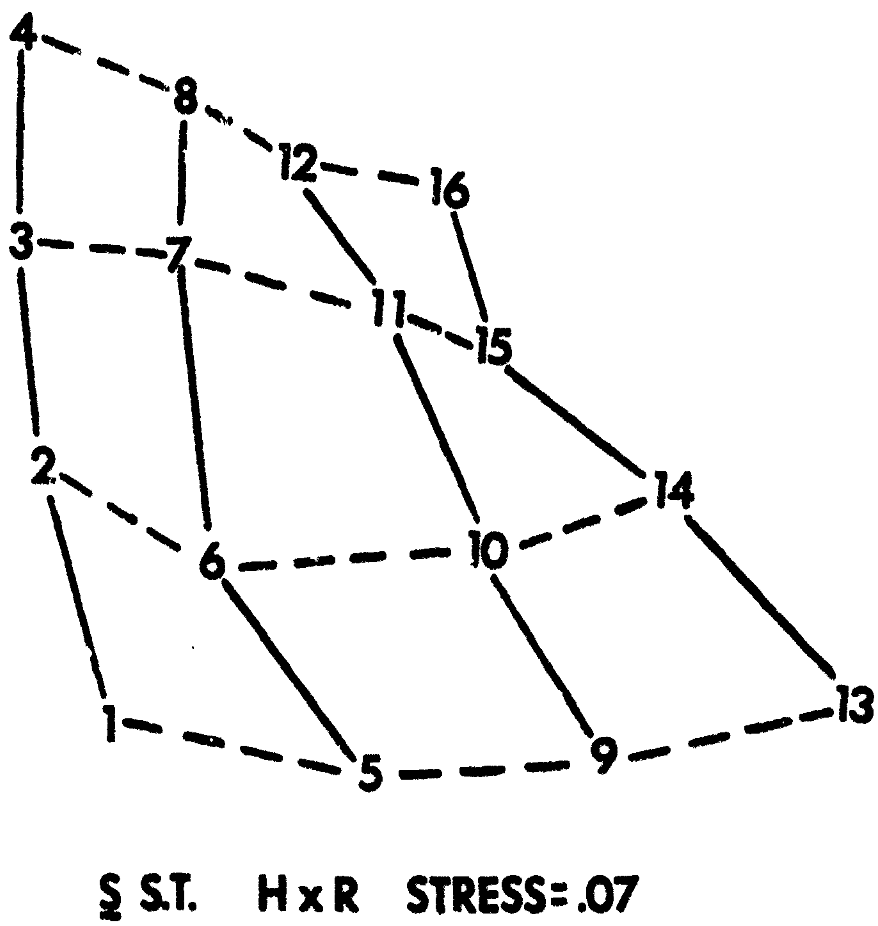
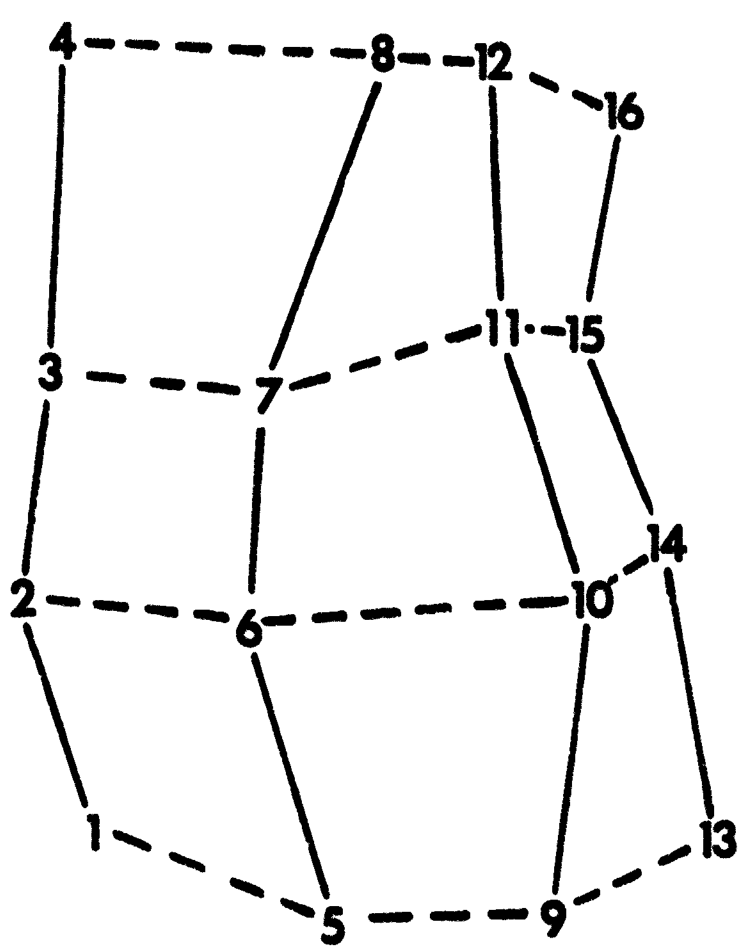


Figure 7: Multi-dimensional scaling configuration of perceived similarities between pairs of triangles for observer S.T. The solid lines connect triangles differing only in height (H). The dashed lines connect trinagles differing only in length of right side (R).



§ S.T. $HR^{.8} \times aR^{.2}$ STRESS=.07

Figure 8: Multi-dimensional scaling configuration of perceived similarities between pairs of triangles for observer S.T. The triangles are topological transformations of the stimulus set of Figure 7.

in Figure 7; that is, the plot is far more rectangular. This plot satisfies a condition of multidimensional scaling termed interdimensional additivity. In fact, the unsystematic deviations from perfect rectilinearity are not significant for this observer.

To summarize, the method that we have developed for isolating the perceived attributes of a stimulus is based on the analysis of the perceived similarities between stimuli varying on two dimensions. Two psychological dimensions are independent if they satisfy the criterion of interdimensional additivity, that is, if differences along each dimension are independent of the level of the other dimension as in Figure 8. If two display dimensions are varied orthogonally and yield similarity judgments satisfying interdimensional additivity, then the physical dimensions correspond to the psychological dimensions; the dimensions are separable. If the orthogonal physical dimensions do not yield similarity judgments satisfying interdimensional additivity, the form of the interaction can be used to derive a new set of stimulus dimensions that will correspond more closely to perceived attributes.

Psychophysical Compatibility and Performance Measures

The present theory has defined dimensional integrality as a property of the mapping of the multidimensional physical specification of a stimulus set into the perceivable psychological attributes of the stimuli. This property of the multidimensional psychophysical mapping, which involves the correspondence between the physical dimensions and psychological attributes, is important enough to require a taxonomic label -- psychophysical compatibility. When the correspondence is high, the mapping will be psychophysically compatible, and the dimensions will be separable. When the correspondence is low, the mapping will be incompatible, and the dimensions will

be integral. The use of the term "compatibility" has been chosen specifically because of its linkage to the classic information processing and reaction time literature (see Fitts and Posner, 1967). Psychophysical compatibility provides a straightforward account of the interference and facilitation obtainable in reaction time experiments as a result of the integrality of the dimension types. It should be noted, however, that the present approach, in contrast to Garner's operational approach described earlier, makes these patterns of results from speeded information reduction tasks a prediction rather than a definition. That is, the present approach explains <u>how</u> integrality <u>leads</u> <u>to</u> filtering decrements and redundancy gains in performance instead of taking these results as part of the definition of integrality.

Information reduction tasks (see Posner, 1964) have classically been defined relative to the arbitrary physical dimensions that an experimenter has chosen to vary in his experiment. However, the type of information required of an observer -- filtering or condensing -- should be defined with regard to the <u>perceived</u> attributes of a set of stimuli. Filtering one perceived attribute from another will be easy, since perceived attributes are by definition independent. If dimensions are psychophysically incompatible, however, filtering on the basis of the physical dimensions requires condensing perceived attributes, since the value of a stimulus on a physical dimension is perceived as a combination of values of those attributes. Thus, only with perfect psychophysical compatibility will the instruction to filter display dimensions be equivalent to filtering the perceived attributes of the stimulus. Redefining integrality as psychophysical incompatibility, then, indicates the basis for finding that integral dimensions are difficult to filter but easy to condense. Similarly, the theory also predicts that the ease of condensing will depend on the

degree to which the condensing rule matches the function relating physical to psychological dimensions.

To test these notions, the triangles that were scaled for the observer whose data were shown in Figures 7 and 8 were used in a series of information processing experiments where his reaction time for various tasks was measured. He was asked to classify these stimuli, from either the compatible set (i.e. those of Figure 8) or from the incompatible set (i.e. those of Figure 7) in various ways. In the unidimensional condition he was presented with subsets of the stimuli to classify that only varied with regard to one of the dimensions. In the orthogonal condition he was asked to classify subsets of the stimuli that varied on both of the dimensions, but his judgments were to be based on only one of the dimensions. In other words, he was asked to filter the relevant dimension from the irrelevant dimension. In the third condition, he was presented with subsets of the stimuli in which the two dimensions of the stimuli were correlated (either negatively or positively) with each other. In these conditions the dimensions are redundant with each other and the extent to which the observer can utilize this redundancy can be taken as an index of how well the dimensions can be condensed. Again, note that the subject of this experiment is the same as the one for whom the psychophysical compatibility was determined in Figures 7 and 8.

The basic result of the experiment is shown in Figure 9. On the left are the data for the psychophysically compatible dimensions (i.e., the non-interacting set). On the right are the data from the psychophysically incompatible dimensions (i.e., the interacting set). The control condition

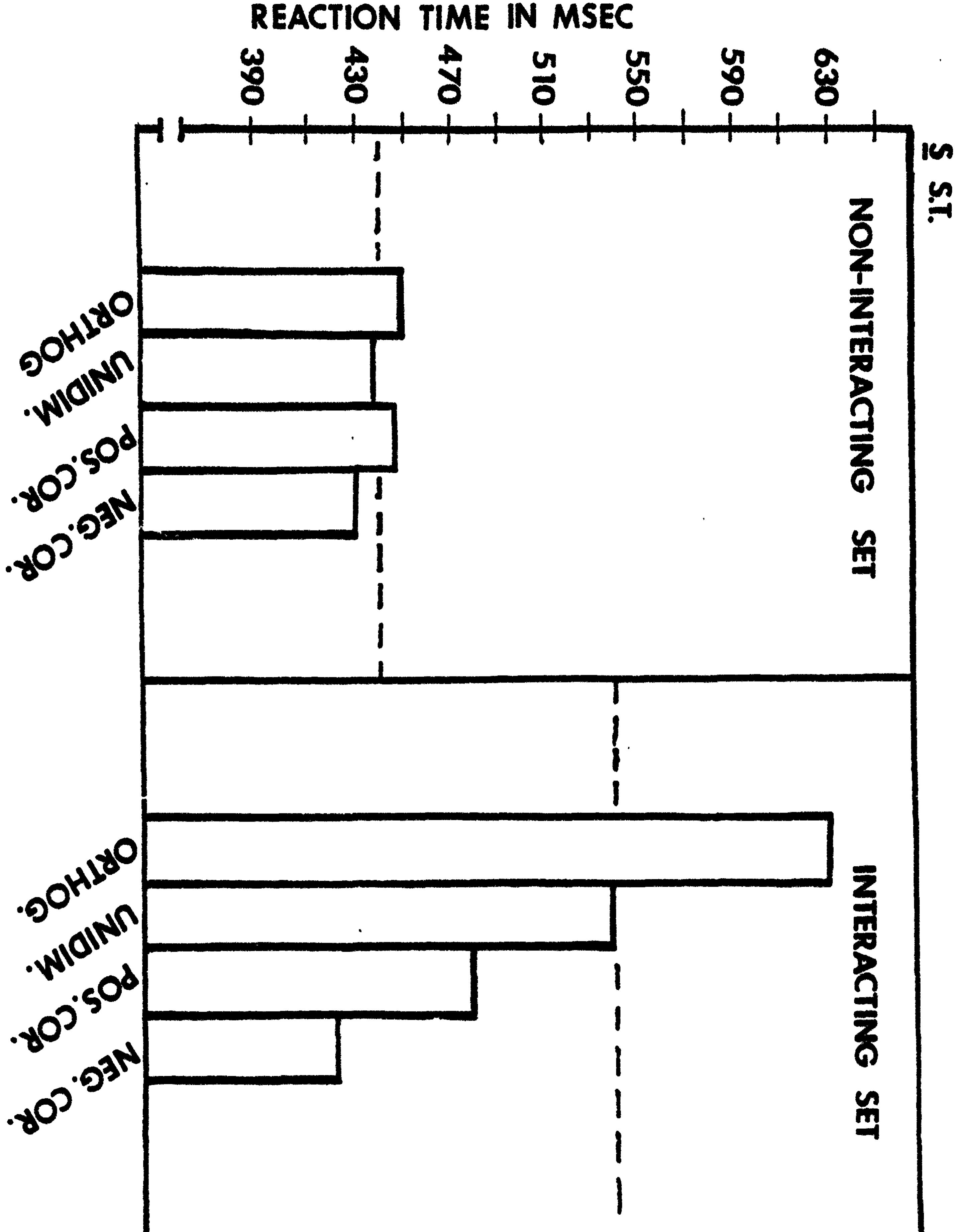


Figure 9: Mean reaction time for speeded sorting of the two sets of triangles

is the unidimensional condition, where there was only one aspect of the stimuli to classify. In each graph the reaction time for this control condition is indicated by the dashed line. Reaction times longer than this value represent decrements in performance, while reaction times shorter than this value demonstrate improved performance. For the compatible set of stimuli neither the orthogonal nor the correlated (i.e., the redundant) conditions differed significantly from the control. However, for the psychophysically incompatible set of stimuli, there was a large decrement in performance for the orthogonal condition and a large gain in performance for the correlated conditions. In other words, the subject found it difficult to filter the relevant from the irrelevant information, but was able to make use of the redundancy of the two dimensions in order to increase his reaction time when the dimensions were correlated. As indicated above, this pattern of results is exactly that which Garner has used in order to define integrality. However, here the pattern is the consequence of independently determined psychophysical mapping.

Limitations of the Psychophysical Approach

As noted earlier, there are at least two limitations to the psychophysical approach to integrality suggested in the present paper. These will be briefly presented in this concluding section.

First, the definition of integrality presented here is intimately related to the notion of interdimensional additivity. Before the present theory can be considered complete, however, it must be shown whether interdimensional additivity alone is sufficient to account for the results described in the last section. It should be noted that the transformation of the physical variables that removed the interaction found in Figure 7 is just one of a potentially infinite number of transformations that could

lead to the kind of rectangularity found in Figure 8. For example, one might think of the possibility of producing rigid rotations of the configuration of Figure 8 in some similarity space. The critical question is: will each of these transformations, given the rectangularity of the configurations, lead to results such as those found in Figure 9? Alternatively, will one of these rotations be a preferred set of axes? Affirmation of the first question (i.e. the demonstration that interdimensional additivity is a sufficient condition for obtaining the results of Figure 9) will lead to the notion that the salient perceptual attributes of a set of stimuli are a consequence of the context of the set of stimuli themselves. However, affirmation of the second question will argue that the salient attributes are a consequence of the particular stimulus domain that is exemplified by the particular set of stimuli used in the experiment. Of course, the question of context dependency is one of the most fundamental questions that can be asked about perceptual processing, and the extension of the present approach in examining this question should be equally fundamental.

Second, data obtained by Somers (1978), in addition to those presented here, indicate clearly the existence of phenomena that a simple psychophysical approach cannot handle easily. In particular, her experiments manipulated the relative discriminability of the dimensions used to define the stimuli as well as their psychophysical compatibility. Her data demonstrate effects on performance of relative discriminability that seem to be quite different from and independent of psychophysical compatibility. Highly discriminable dimensions seem to acquire a salience that can dominate performance regardless of their interaction with other stimulus dimensions. This dominance of performance seems to indicate that some form of attentional mechanism will be needed to account for the ability

of the subject to switch from one dimension to another, when their discriminability varies greatly. Thus, it seems clear that some process account, in addition to psychophysical factors, will be needed to bring any form a completeness to the definition of integrality.

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